

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

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0280

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE		3. REPORT 15 FEB 1998 - 14 MAR 2002 Final Report	
4. TITLE AND SUBTITLE (DEPSCOR 97/98) ADAPTIVE OPTICS, LLLFT INTERFEROMETRY, ASTRONOMY				5. FUNDING NUMBERS 61103D 3484/BS	
6. AUTHOR(S) DR FRIEDMAN					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF PUERTO RICO-CENTRAL ADMINISTRATION FACUNDO BUESO BLDG ROOM 304 RIO PIEDRAS PR 00931				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE 4015 WILSON BLVD SUITE 713 ARLINGTON VA 22203				10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-98-1-0290	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) We propose to build a three telescope Michelson optical interferometer equipped with wavefront compensation technology as a demonstration and test bed for high resolution Deep Space Surveillance (DSS) and Astronomy. Each telescope will have a liquid crystal (LC) Adaptive Optics (AO) phase retarder capable of providing diffraction or near diffraction limited operation. We will combine the wavefronts from the three telescopes using a conventional beam recombination system and acquire and track the fringes formed with a Low Light Level Fringe Tracking system (LLLFT). The telescopes, fringe tracker, a photon counting (Baker) camera, and LC devices and associated wavefront sensors are novel ideas currently under development at the USAF's Phillips Laboratory (PL) for DSS and this combination should yield a state-of-the-art system equal or superior in performance to the best of the current generation of AO and Interferometric systems but for a few percent of the cost.					
14. SUBJECT TERMS				15. NUMBER OF PAGES	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED		19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	
				20. LIMITATION OF ABSTRACT UL	

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Final Report

Adaptive Optics Interferometry

ABSTRACT:

We propose to build a three telescope Michelson optical interferometer equipped with wavefront compensation technology as a demonstration and test bed for high resolution Deep Space Surveillance (DSS) and Astronomy. Each telescope will have a liquid crystal (LC) Adaptive Optics (AO) phase retarder capable of providing diffraction or near diffraction limited operation. We will combine the wavefronts from the three telescopes using a conventional beam recombination system and acquire and track the fringes formed with a Low Light Level Fringe Tracking system (LLLFT). The telescopes, fringe tracker, a photon counting (Baker) camera, and LC devices and associated wavefront sensors are novel ideas currently under development at the USAF's Phillips Laboratory (PL) for DSS and their combination should yield a state-of-the-art system equal or superior in performance to the best of the current generation of AO and Interferometric systems but for a few percent of the cost.

The enhanced capabilities should find application in many areas but are primarily targeted at the identification, characterization, and imaging of Low Earth Orbit (LEO) and Geosynchronous (GEO) satellites as well as Near Earth Objects (NEOs) for Deep Space Surveillance. NEOs are represented by Earth crossing asteroids and comets that represent a possibly significant threat to the Earth. Independent use of the telescopes will allow discovery of new and lost objects. Demonstration of the system and subsystems will significantly enhance our surveillance capabilities.

The astronomical capabilities of a very high resolution system are self evident and will include significant goals of the Congressionally mandated Origins program and other high resolution studies; such as planetary mapping.

In addition demonstration of the LC [1-5] device will make it possible to inexpensively upgrade existing earth based telescopes so they can operate at their theoretical diffraction limit and equal the resolving power of space based instruments such as the Hubble Space Telescope (for far less initial cost, maintenance, and much lower vulnerability). This will enable ground based instruments to observe satellites, astronomical threats, and objects of astronomical interest in unprecedented detail.

INTRODUCTION

Systems with milliarcsecond resolution are required to image a large number of astronomical and space based objects. Deep Space Surveillance (DSS) needs dictate very high angular resolution to identify and characterize satellites, especially those in high and Geosynchronous orbits. Optical interferometers are being built to achieve this high resolution (NPOI, COAST, the Two Kecks, IOTA, SUSI, GI2T, and CHARA) and are the direction necessary to go for any reasonable increases in resolution. We propose to build a system which will allow us to co-phase an array of telescopes in the presence of atmospheric turbulence at low light levels. This kind of instrument will be able to detect and track objects fainter than 10^{th} magnitude and with reasonable expectation, geosynchronous satellites and other objects at 12^{th} to 14^{th} and possibly 15^{th} magnitude [6-16]. The LLLFT will also be a transportable technology with scaling in cost only applicable to differences in the optical path compensation required. If phasing is partially accomplished with optical fibers [17-19], as we propose, it will also be very inexpensive as opposed to optical trombones. This is a critical area of research we plan to address with this system. The coupling of an atmospherically degraded signal into optical fibers has been addressed with only limited success and we will directly address the issue with an appropriate dedicated test bed.

Such a device working in this faint visual magnitude regime together with its inherent high resolution would be useful in examining certain classes of objects of interest to DoD inaccessible with existing systems. The fringe tracking system for such a device must allow for mirror and system vibrations, atmospheric effects, detector noise, and photon noise, among others [6-16, 20-29]. Several groups, most notably, COAST and NPOI have built such instruments and achieved phase closure using differing fringe tracking systems although not in the low light level regime in which we wish to operate and required to observe GEOs.

To build such a device successfully, the fluctuations in the complex visibility due to fluctuations in physical parameters must be quite well understood. Specifically, the effect of an arbitrary fluctuating physical parameter must be directly traced to the fluctuation in the complex visibility [20-29]. We must be able to model physical processes that maintain coherence within the single pupil; vibrations in the optical train, atmospherically induced phased delay, and residual errors in the fringe tracker. Photon fluctuations, finite spectral bandwidths, Optical Path Difference (OPD) fluctuations, and inter-pupil photon correlations must be analyzed and applies equally well to either image plane or pupil plane measurements [6-16, 20-29].

Two points must be made. First, the van Cittert-Zernike theorem demonstrates the complex visibility to be a measurement of the spatial spectrum of the object in only a narrow regime of physical parameters. However, use of the complex degree of spatial coherence to estimate the complex visibility is valid over a much broader regime. Hence, use of a Michelson interferometer to measure the spatial spectrum of an object is valid over a much broader regime than the van Cittert-Zernike theorem would suggest. Second, using second order coherence theory to describe a Michelson type interferometer keeps the analysis independent of the beam recombination system. That is, the device that recombines the light is not incorporated into the analysis. From the point of view of

Michelson interferometry, this analysis is useful for either pupil plane or image plane measurements of the fringes (10, 20-29).

The inverse dependence of the magnitude and phase on the bandwidth of the light must be emphasized. In Imaging it is well known that the phase of the spectrum is more important in reconstructing an object than the magnitude, while in astrometry, the magnitude is the important quantity. Hence, for astrometric measurements, a small bandwidth is needed. If the measurements are for imaging, a large bandwidth is needed and that is the reason our system will be optimized for white light.

The zero OPD of an optical interferometer can be calibrated quite easily. The bandwidth of the emitted radiation of a laser diode is a function of the input current. The laser diode is inserted into the beam train at high current (lasing \rightarrow narrow bandwidth, long coherence length), the OPD is zeroed, the current is lowered (the coherence length decreases) and the system is re-zeroed. The current is thus lowered until the light intensity from the laser diode is barely visible by the detectors. At this point the laser diode is well below threshold and is emitting a broad spectrum. The bandwidth of this spectrum is close enough to the bandwidth of visible light, that when the full visible spectrum (white light) is inserted into the optical system, the zero for the white light is easily found (J. Baker, personnel comm.)

The initial configuration of the interferometer can be upgraded to include more telescopes and variable positions to provide improved resolution of the targets and is a straight forward process. The technical knowledge for parts of the system has been developed during the last few years in the Phillips Laboratory (now Air Force Research Laboratory which we shall continue to call Phillips, or PL) and is ready to be placed on a prototype in the field. Laboratory demonstration of the LLLFT has recently been accomplished at PL/LIMI.

Liquid Crystal Spatial Light Modulators (LC-SLMs) are being developed as an alternative to the deformable mirrors in adaptive optics systems. For interferometers incorporating several adaptive optics systems, LC-SLMs are a particularly suitable technology because they are a) transmissive and so relatively easy to install and b) of relatively low cost. They are also light weight and suitable for space applications. Their transmissive nature makes them suitable for placement in existing systems. Current costs are about \$30 K per LC array (although this is predicted to fall) compared with $> \$100$ K for a deformable mirror. Associated control electronics for complete systems are comparable.

There are, of course, some disadvantages of LC-SLMs when compared to deformable mirrors, although we are confident that these can be overcome with the ongoing DoD investment in device development and materials research. This is particularly acute in the temporal correction bandwidth and is being addressed in the materials research program. Repair is much easier with the LC devices compared to deformable mirrors as is integration into existing systems.

A number of different groups have been investigating the use of LC-SLMs, [1-3]. The earliest work involved modifying liquid crystal displays (TVs) which were not designed to be used as precision optical elements. The most recent work has been undertaken by the Phillips Laboratory, the University of Durham, UK, and Meadowlark Optics, Boulder, CO. The team has demonstrated

that precise wavefront control can be achieved, via the quantitative production of Zernike wavefront aberrations [4] and that the system can produce enhanced image quality in a closed loop system using a Shack-Hartmann wavefront sensor [5]. We plan to coordinate closely with Meadowlark on the production of the LCs, relevant materials research, and infrastructure development.

Once proven in the field the AO system will be readily cloneable for transport to other installations at essentially the same cost regardless of the size of the telescope. Infrastructure development in this engineering area will be very valuable in many areas outside of astronomy and DSS. After development and proof of concept on a 24"-30" telescope it should be directly transferable to telescopes of several meters with no scaling factor. This is independent of its use on our interferometer. If funded we fully intend that this facility serve as the AO and LLLFT test-bed for the proposed Magdalena Ridge Observatory (MRO).

Jeff Baker, working under contract to the Phillips Laboratory has just developed a new camera concept to replace the \$400,000 MAMA camera on the test-bed wavefront sensor. It can be made from off-the-shelf hardware and is currently being designed. Preliminary component tests have been conducted to our satisfaction and hopefully a prototype will be tested within the next few months.

Wavefront sensor camera examples

a) Gen III	35k
b) MIT	71k
c) homemade MAMA	100k
d) PAPA	100k
e) commercial MAMA	400k
f) Baker	15k

Camera option a) is the minimally acceptable level of performance. It compromises the LLLFT but is sufficient for much of the science and most of the testing. Option b) is a state-of-the art CCD camera from MIT Lincoln Labs and is far better but is still of less quality than the MAMA camera being used on the present test bed. MAMA cameras are approximately \$400,000 but we feel we can put together our own as Masters or Ph.D. research projects within three years for approximately \$100,000 each. The Baker cameras will cost about \$15,000 each and should be equivalent to or exceed the MAMA in performance. A last option is a PAPA camera commercially available for about \$100,000 each. These detectors are the heart of the LLLFT and AO systems, which are the keys to performance that exceeds currently available systems. These inexpensive photon counting cameras will have many applications in DoD. Infrastructure development in this area would be very rewarding in terms of developing technologies.

The Baker camera consists of an Ultra-Blue Enhanced GEN III image intensifier optically coupled to an 840Hz frame rate, 128x128 element Dalsa camera. The camera is MAMA and PAPA like, being low noise, photon counting, but better since it will use a

45-50% quantum efficiency photocathode. Total camera cost, with low F number coupling optics, is approximately \$6.5k, and should outperform state-of-the-art CCD cameras. Control electronics, I/O, frame grabbers and associated equipment will make the entire system price about \$15K; less than half of the next cheapest, but minimally acceptable alternative (J. Baker, per. Comm. a). This will be a very attractive option for many applications within DoD and industry..

The use of single mode(SM) optical fibers for optical interferometry has been suggested by several authors [17]. The reason for such interest resides in the characteristics of such fibers. They act as perfect spatial filters, have almost loss-less power transport, are readily available, and are very inexpensive. However the experimental part of such work is much behind the theory due to the extremely low coupling efficiency between an atmospherically corrupted image and a SM fiber. The USAF Phillips Laboratory is among the few groups that has experimental know-how in coupling starlight into SM fibers, and the only to have performed a link between two large telescopes using SM fibers [18,19]. The promise of SM fibers for interferometry is to reduce the level of Adaptive Optics (AO) required, reduce dramatically the alignment requirements and the cost of some of the beam transport elements. Proper installation of fibers can reduce the need for OPD compensation by maintaining constant optical paths from the individual elements while reconfiguring the array. Compensation of Optical Path Length (OPL) can also be achieved in a very inexpensive way with the fibers using piezoelectric stretchers [18,19]. While a few microns of OPL has been demonstrated several times, in laboratory tests millimeters level of compensation have been achieved. By applying these well developed techniques we hope to prove much greater lengths of OPL compensation can be achieved in a cascade type system. This will be an extremely important area of research carried out on the interferometer. Solution of this problem will engender great cost savings in many existing system. We plan to address the coupling issue directly; the applications of this aspect are critically important to many optical technologies in and out of DoD.

A fiber based recombination beam offers a straight forward way to achieve quadrature for phase extraction. Transfer to existing systems should relatively inexpensive.

Furthermore, the Phillips Lab team is working on developing new concepts, like the multi-core single mode (MCSM) fibers that may increase dramatically the coupling efficiency with SM fibers. This will make the use of fibers even more appealing for a practical optical interferometer (S. Restaino, per. Comm.). One of our investigators has expertise in Physics and Engineering and has been working with fibers for several years and we feel he will be key in attacking this problem.

RESEARCH TO BE UNDERTAKEN and TECHNICAL MERIT

Scientific Objectives:

The research to be undertaken can be broken down into three general areas. All of these areas are significant on their own merits but the combination is very powerful. 1) DoD related surveillance capability, testing, and implementation and; 2) optical research that includes fiber applications, LLLFT , wavefront sensor

development, adaptive optics using LCs, electronic camera development, system integration and control, and development of portable units. This will be the first full scale field implementation of the parts and integrated system; 3) Basic high resolution astronomical research. All of these areas have strong DoD applications; even the astronomy LLLFT and AO as it will include the detection and characterization of NEOs such as asteroids and comets with orbits that intersect that of the earth's.

The construction of the system will develop infrastructure for astronomy, optics, digital engineering, optical fibers, high speed tracking, LCs, wavefront sensors, and digital cameras. Each of these technologies has wide application outside the specifics of this experimental apparatus for DoD and the academic and commercial communities. We will acquire not only a world class astronomical instrument, sensitive surveillance device, and optical test-bed; but also state-of-the-art knowledge and capability in each of these areas of infrastructure development. Significant materials research can be done in LC materials as well.

The project can be thought of as immediately capable of high resolution deep space surveillance, as an excellent field demonstration and test bed for new devices and techniques in low light level adaptive optics and fibers and high resolution astronomy.

Our objectives mimic the direction of the research thrusts. Number one; we hope to have a state-of-the-art high resolution adaptive optics DSS and astronomical instrument with which to carry out a broad range of demanding surveillance and observational programs. The availability of an adequate test bed for DSS is at a premium and it is difficult to get time on these systems to test new equipment. In addition requisite high resolutions are just now becoming available on a very limited basis and essentially no DoD capability exists at the low light levels needed to detect, track and image GEOS from the ground. Very high resolution astronomy is also available on only a very limited basis and at very high cost. Interests within the group include Solar system planetary mapping alone and in conjunction with the Arecibo Observatory Radar, Super Nova Remnants and Pulsar coincidence, galaxy mapping, discovery and imaging of external planetary systems for Origins research, stellar disks, cataclysmic variables and contact binaries to name a few. We also have many contacts at the Arecibo Observatory and elsewhere with interests in coordinated multi-frequency observations.

We also should be able to demonstrate a significant improvement in deep space surveillance capability. If the LLLFT and wavefront sensor for the Love LC device can push our adaptive optics interferometric system to 12-14th magnitude, as it has been designed to do, it will be possible, for the first time, to image GEOs from the ground. An interferometer is necessary for the required resolution but the system must also be able to compensate for the atmosphere at light levels several magnitudes fainter than is currently available. The new Air Force 3.6 meter telescope currently being assembled on Mt. Haleakela on Maui in Hawaii will only be able to attain 7th magnitude with its AO system [30]. The individual telescopes can also be considered as independently operable affordable

adaptive optics prototypes that can be cloned for wide distribution. They will be designed with surveillance/detection capabilities.

The individual telescopes will have fast tracking capabilities for LEOs, and can easily be upgraded for aircraft and missiles. They should have sufficient resolution and field of view to detect and characterize NEOs and manmade objects including newly launched and/or unidentified satellites. They are also of sufficient size coupled to near diffraction limited resolution to do significant astronomy independently. This will give use a three telescope observatory under computer control capable of extensive surveys and targets of opportunity. This capability will enable us to utilize one or more of the telescopes while repairs and upgrades are being made to the interferometer or individual elements and more than double its capacity for science and surveillance.

We intend that the system be readily (and constantly) available to test advanced adaptive optics concepts. Several of the subsystems are newly developed at PL and have never been tested in the field. The proof of these technologies should be considered a significant goal of the instrument. It should be considered a dedicated test system for new technologies as they fit into the observational program. We intent to have a truly multi-purpose facility.

We envision a new role for fast tracking adaptive optics systems in interdiction efforts. Acquisition and tracking of low flying aircraft is very important to efforts of the customs service and its military counterparts. Portability and affordability are primary concerns. The telescopes given look-down capability may also be of value to the INS for surveillance of sea craft.

GRADUATE EDUCATION AND TECHNICAL PERSONEL

I plan to support 2 graduate students per year. If possible we would involve others if additional funding sources can be found. Certainly research opportunities abound within the project. The electronic component construction alone could support several graduate students; camera development more, and wavefront sensors more. All areas addressed by this research can be considered critical and valuable technologies. Education in these disciplines should be very valuable in the marketplace with increased emphasis on adaptive systems of all types, fiber communications and computing, and electronic control. I also hope to have undergraduates work on the project especially on the telescope and array construction and testing.

The base collaboration within UPR will have 4 people in Physics plus our two technicians. We will actively interact with others within Physics and Engineering and several astronomers at the Arecibo Observatory. There will be very active involvement of 6 scientists and engineers at PL and one at the U. of Durham, UK. Several additional technicians will be involved at UPR and PL.

DoD ENVOLVMENT PL (with BMDO Applications)

The project; in its elements and overall design was developed and initially tested at PL and continues to be an area of active interest. It is one of the core areas in the Deep Space Surveillance Branch of the Lasers and Imaging

Directorate at Kirtland AFB.. We will have 6 active collaborators there that will help design the system for AF needs, and will continue to use it to develop and test evolving concepts and hardware. Design and consultations will still go through PL and in many cases will be initiated by PL. The instrument will serve as a dedicated test-bed for future PL experiments and innovations. DSS capabilities are central to all design elements. The AO system will not only prove PL designs it should serve as the test bed for a BMDO/WSMR AO system to be built for a 2 x 2.4 meter and 0.75 meter telescope interferometer in the planning stages for an Observatory in New Mexico (MRO) that is being designed to BMDO/WSMR specifications for missile tracking, kill assessment, and DSS needs. The whole array may eventually be integrated into the MRO to better serve the needs of the DoD partners and Astronomy interests. UPR is a member of the Consortium involved in the design and management of the proposed facility.

PL will also test fiber optics ideas and wavefront sensors on the project proposed under this announcement for DSS and Space based systems.

FACILITIES:

We have in house machine and electronics shops and test lab space. We have outdoor test facility space. We propose a permanent installation at a site to be determined to be built by the university in the future after completion of the construction and testing phases. This would entail the construction or renovation of a structure we estimate will cost ~ \$30k. This structure will house the combining optics bench and control computers as well as serve as a storage area for the telescopes when they are not in use. We have several sites in mind that are UPR or PR controlled property and are planning site surveys in the coming year. As an alternative we will consider a high site in New Mexico where two 2.4 meter telescopes are to be built and UPR is a consortium member charged with operations and management (the MRO). This observatory is already being designed with interferometry specifically in mind.

PL has several laboratories that will be available for testing and construction projects.

We hope to perform large scale testing and integration at the university before final placement at a permanent research station owned or operated by the University.

BUDGET RATIONAL :

This budget effort is primarily directed towards the construction of the instrument. Most of the funds are direct equipment purchases and most of the rest is for salaries for graduate students, lab technicians, and faculty summers to work on the project. The only additional money is \$10000 per year for travel. As this is a sophisticated collaboration with the PL a lot of travel between the two working groups will be required. The DoD needs an inexpensive mobile high resolution system for many surveillance needs. The modular nature of this system make it adaptable for this purpose and this system can serve as a prototype and

test platform for other such systems. The cost is minimal and possible benefit great. Engineering Infrastructure development in the DoD critical areas of Optics, Adaptive Optics, wavefront sensors, electronic control, fast feedback electronic systems, and wavefront compensation will be extensive. Materials research in LCs will be extensive and produce very versatile devices not only for wavefront compensation but in other dynamic areas. Industrial applications are starting to emerge for adaptive optics in harsh environments and fiber optics is a burgeoning field.

The project will provide many opportunities in Graduate education for research and capability enhancement. The students graduating from research associated with this project should be capable of filling pressing needs in DoD DSS, Space based systems, Adaptive Optics, Optical fiber communications, fast feed back control systems, signal characterization, interferometry, optical system integration, computer control, and high resolution astronomy as well as other areas.

Specifically the funds will be for the construction of 3 24"-30" telescopes(\$75k), 3 wavefront sensors and LC wavefront compensation devices(\$255k), the optical table with necessary equipment for the Michelson Interferometer, fringe tracker and detectors(\$120k). Additional funds are for fiber equipment and control and integration electronics. Major equipment purchases are over half of the budget but amount to little more than the cost of a single MAMA camera(\$400k). The list includes 5 cameras of our design of equal quality; one for each wavefront sensor and two for the optical bench.

OTHER PARTIES TO RECEIVE PROPOSAL (or parts thereof) Cotrell Research Corp.; NASA, NSF, DoD DURIP

EXTERNAL SUBCONTRACTS; none